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INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter II of the Patent Cooperation Treaty)

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference 19877S	FOR FURTHER ACTION See Form PCT/IPEA/416	
International application No. PCT/FI2004/000532	International filing date *(day/month/year)* 14.09.2004	Priority date *(day/month/year)* 26.09.2003
International Patent Classification (IPC) or national classification and IPC See Supplemental Box		
Applicant ELEKTA NEUROMAG OY et al		

1. This report is the international preliminary examination report, established by this International Preliminary Examining Authority under Article 35 and transmitted to the applicant according to Article 36.
2. This REPORT consists of a total of 6 sheets, including this cover sheet.
3. This report is also accompanied by ANNEXES, comprising:
   a. ☒ *(sent to the applicant and to the International Bureau)* a total of 13 sheets, as follows:
      - ☒ sheets of the description, claims and/or drawings which have been amended and are the basis of this report and/or sheets containing rectifications authorized by this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions).
      - ☐ sheets which supersede earlier sheets, but which this Authority considers contain an amendment that goes beyond the disclosure in the international application as filed, as indicated in item 4 of Box No. I and the Supplemental Box.

   b. ☐ *(sent to the International Bureau only)* a total of (indicate type and number of electronic carrier(s)) ________________, containing a sequence listing and/or tables related thereto, in electronic form only, as indicated in the Supplemental Box Relating to Sequence Listing (see Section 802 of the Administrative Instructions).
4. This report contains indications relating to the following items:
   - ☒ Box No. I Basis of the report
   - ☐ Box No. II Priority
   - ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - ☐ Box No. IV Lack of unity of invention
   - ☒ Box No. V Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - ☐ Box No. VI Certain documents cited
   - ☐ Box No. VII Certain defects in the international application
   - ☐ Box No. VIII Certain observations on the international application

Date of submission of the demand	Date of completion of this report
26.04.2005	20.12.2005
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Form PCT/IPEA/409 (cover sheet) (April 2005)

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

International application No.
PCT/FI2004/000532

Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of: Cover sheet

INTERNATIONAL PATENT CLASSIFICATION (IPC):

A61B 5/04 (2006.01)
G01R 19/00 (2006.01)

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

International application No.
PCT/FI2004/000532

Box No. I **Basis of the report**

1. With regard to the **language**, this report is based on:

- [x] the international application in the language in which it was filed
- [ ] a translation of the international application into ____________ , which is the language of a translation furnished for the purposes of:
  - [ ] international search (Rules 12.3(a) and 23.1(b))
  - [ ] publication of the international application (Rule 12.4(a))
  - [ ] international preliminary examination (Rules 55.2(a) and/or 55.3(a))

2. With regard to the **elements** of the international application, this report is based on *(replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report):*

- [ ] the international application as originally filed/furnished
- [x] the description:
  - pages ____________ as originally filed/furnished
  - pages* 1-9 received by this Authority on 12-12-2005
  - pages* ____________ received by this Authority on ____________
- [x] the claims:
  - pages ____________ as originally filed/furnished
  - pages* ____________ as amended (together with any statement) under Article 19
  - pages* 10-13 received by this Authority on 12-12-2005
  - pages* ____________ received by this Authority on ____________
- [x] the drawings:
  - pages 1 as originally filed/furnished
  - pages* ____________ received by this Authority on ____________
  - pages* ____________ received by this Authority on ____________
- [ ] a sequence listing and/or any related table(s) – see Supplemental Box Relating to Sequence Listing.

3. [ ] The amendments have resulted in the cancellation of:

- [ ] the description, pages ____________
- [ ] the claims, Nos. ____________
- [ ] the drawings, sheets/figs ____________
- [ ] the sequence listing *(specify)*: ____________
- [ ] any table(s) related to the sequence listing *(specify)*: ____________

4. [ ] This report has been established as if (some of) the amendments annexed to this report and listed below had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).

- [ ] the description, pages ____________
- [ ] the claims, Nos. ____________
- [ ] the drawings, sheets/figs ____________
- [ ] the sequence listing *(specify)*: ____________
- [ ] any table(s) related to the sequence listing *(specify)*: ____________

* *If item 4 applies, some or all of those sheets may be marked "superseded."*

Box No. V **Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement**

1. Statement

Novelty (N)	Claims	2-9, 11-17	YES
	Claims	1,10,18	NO
Inventive step (IS)	Claims		YES
	Claims	1-18	NO
Industrial applicability (IA)	Claims	1-18	YES
	Claims		NO

2. Citations and explanations (Rule 70.7)

The problem solved is a more efficient way of calculation in converting measurement signals emitted from electromagnetic fields.

Reference is made to the following documents:
D1:US5269325
D2:EP10302160
D3:US6370414
D4:US6374131
D5:EP0982597
D6:EP0632353
D7: 'Multipole expansions of electromagnetic fields using Debye potentials', C. G. Gray, American Journal of Physics,Vol. 46, pp. 169-179, 1978.

D1 through D6 each disclose the method and the device of determining current distribution of an object by measuring the magnetic fields in the vicinity of the object, subsequently calculating the signals as from a set of virtual sensors.

D7 discloses a method of multipole expansions of electromagnetic fields.

The invention according to claims 1, 10 and 18 is stated by the technical features: (i) converting signals into orthogonal signals from a set of virtual sensors, and (ii) determining the current distribution based on the virtual sensors. All technical features are known from each of D1 through D6. The applicant states that D5 and D6 are irrelevant. However, D5

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Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of: Box V

discloses a method of measuring weak signals and applying virtual channels [0044]. D6 describes the measurement of a non biological object. Present claims 1, 10 and 18 are not directed to any particular kind of object. D6 further describes virtual sensors. Accordingly, all cited documents are relevant.

The applicant also states that the source model needs no further regularisation and that no statistical analysis is required. However, none of the technical features in the independent claims implement those effects.

As to the argument that the equations in D7 are not presented in a straightforward manner, this is neither the case in the independent claims. On the contrary, claim 1 only contains the desideratum of "a predetermined function basis to be efficiently calculated".

The invention claimed in claims 1, 10 and 18 does consequently not fulfil the requirement of novelty.

The invention according to claims 2 and 11 differs from what is known from for instance D1, regarded as the document that is closest in describing the invention, by stating the use of multipole expansion of the field. The problem solved is an alternative way of calculation that is faster and makes the mathematical operations simpler.

Faced with the problem of an alternative way of analyzing the signals, the person skilled in the art knows a solution from D7. D7 addresses multipole expansions of electromagnetic fields. Since D1 and D7 are both applied to electromagnetic fields, it is considered obvious that a person skilled in the art would combine the information and arrive at the invention claimed in claims 2 and 11.

The features stated in the remaining claims are technical features considered known from the cited documents or are general common knowledge for a person skilled in the art, for instance claims 3-6 and 12-14. Claims 7-9 and 15-17 state features that differ from what is disclosed in D7. However, the difference does not exhibit a technical character. The

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Supplemental Box

In case the space in any of the preceding boxes is not sufficient.
Continuation of: Box V

difference is merely a mathematical theory, and as such it does not involve an inventive step (PCT Rule 39 (i)).

Accordingly, the inventions claimed in claims 2-9 and 11-17 do not fulfil the requirement of inventive step.

The invention is industrially applicable.

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12-12-2005

METHOD FOR USING A MULTI-CHANNEL MEASUREMENT SIGNAL IN SOURCE MODELLING

FIELD OF THE INVENTION

The present invention relates to a new and advanced method for using a multi-channel measurement signal in source modelling. In particular, the present invention relates to a new way of converting the measurement signals measured using a multi-channel measuring device that measures a curl free and divergence free vector field into a form optimal from the standpoint of the source modelling.

BACKGROUND OF THE INVENTION

The electrical operation of an object to be examined can be examined e.g. by measuring the magnetic field produced by the electric currents of the object using sensors placed outside the object. The modelling of a source distribution thus obtained based on the measured signals is, however, very difficult because each magnetic field distribution can be produced by many different source distributions. In other words, a source distribution cannot be solved unambiguously based on the measured signals, so to solve the problem, different restrictive conditions must be set, such as some parametric model based on prior information for a current, or a non-parametrised norm restriction.

For the non-parametrised modelling of a continuous current distribution, minimum norm estimates are usually used, in which there is an attempt to explain a signal measured using a multi-channel measurement device with a current distribution whose norm is as small as possible. As the norm, usually an L1 or L2 norm is selected, of which the previous is the sum of the lengths of the current elements over the selected

volume, and the latter is the sum of the squares of the lengths of the current elements over the selected volume. The calculation of the minimum norm estimates has been described e.g. in publications "Interpreting magnetic fields of the brain: minimum norm estimates", M.S. Hämäläinen et al, Medical & Biological Engineering & Computing, Vol. 32, pp. 35-42, 1994, as well as "Visualization of magnetoencephalographic data using minimum current estimates", Uutela K. et al, NeuroImage, Vol. 10, pp. 173-180, 1999.

Conventional minimum norm estimates involve inherent problems such as slowness of calculation and susceptibility to noise. For example, in the case of an L2 norm, one needs an inverse matrix of matrix G, whose element (i, j) contains the inner product of the lead fields of the ith and jth measurement sensor, so one must calculate these inner products for each pair of sensors. The lead field is so determined that the signal measured by a sensor is the projection of the current distribution for the lead field of the sensor in question. The noise problems are due to the fact that matrix G calculated for the sensors is susceptible to noise, so in the calculation of its inverse matrix, regularisation is needed in the practical situations.

Regularisation methods, such as the truncation regularisation of the singular value decomposition, usually are non-intuitive, and usually also to be solved for each case specifically. A regularisation of the wrong type may lead to an erroneous modelling result.

Therefore, source modelling nowadays still involve problems such as the hardness and slowness of the computation, the possible errors caused by noise, as well as the case-specificity due to the regularisation. Further, as stated above, the regularisation may

cause considerably errors to the final computation result.

OBJECTIVE OF THE INVENTION

The objective of the invention is to eliminate the drawbacks referred to above, or at least significantly to alleviate them. One specific objective of the invention is to disclose a new type of method which can be used to considerably lighten and accelerate the computation associated with the modelling of a continuous current distribution, as well as to lessen the problems with noise.

As for the features characteristic of the invention, reference is made to them in the claims.

DESCRIPTION OF THE INVENTION

The present invention relates to a new kind of manner of determining the continuous current distribution of an object being examined using basis vector components of signal space calculated from the measured signals. The components in question have been so selected that they describe the features, as independent as possible, of the current distribution being examined, which enhances the computation and makes it more accurate.

The basic idea of the invention is that because the computation of the inner products of the sensor fields is heavy and difficult using a conventional set of sensors, it is worth using a special set of sensors, whose lead fields are orthogonal and, if possible, to be analytically computed. In principle, this can be implemented by a suitable physical set of sensors. As a suitable physical set of sensors is, however, often quite difficult to manufacture, it is, in most of the cases, advantageous to use virtual sensors computationally generated from a conventional set

of sensors, i.e. the measurement signals are converted into other ones by a suitable conversion so that they correspond to the signals that the virtual measurement device would have measured. At the same time, it is possible, if necessary, to eliminate the signals associated with external interference. This conversion has been described e.g. in patent application FI20030392, which is incorporated herein by reference. After the conversion, the source modelling is performed in an optimal manner using the basis vector components of the signal space instead of the actual measurement signals. One substantial feature of the invention is that after the conversion, the source model need not be any more regularised.

Thus, the present invention relates to a method for determining the current distribution of an object by measuring the magnetic fields in the vicinity of the object using a multi-channel measurement device. Advantageously, at least one measurement sensor corresponds to each channel, and the object is approximated by a spherically symmetric conductor. The object can be e.g. a human being's head.

According to the invention, a multi-channel measurement signal corresponding to each measurement sensor is converted into the signals of a predetermined set of virtual sensors, and the current distribution of the object being examined is determined by depth r from the signals of the set of virtual sensors in a beforehand selected orthonormal function basis. In that case, the estimation of a current distribution is fast and robust. Further, to achieve the set of signals corresponding to the set of virtual sensors, a multi-pole expansion is calculated from a multi-channel measurement signal. A multi-pole expansion can be calculated in two ways: by taking into account the magnetic fields emitted by sources outside the object being measured, or by ignoring them.

Advantageously, as the orthonormal function basis, a basis with the following form is selected:

$$\vec{J}(\vec{r}) = \sum_{l=0}^{L} \sum_{m=-l}^{l} c_{lm} f_l(r) \vec{X}lm(\theta,\varphi) \text{ ,}$$

wherein $f_l(r)$ is a radial function to be freely selected and $\vec{X}_{lm}(\theta,\varphi)$ is so-called vector spherical harmonic. In that case, it is possible to place the function basis into a current distribution equation, and the coefficients of the current distribution are analytically solved based on the equation:

$$c_{lm} = \hat{\gamma}_l M_{lm} \left[\int_0^R r^{l+2} f_l(r) dr \right]^{-1} \text{ ,}$$

wherein $\hat{\gamma}_l$ is a constant associated with order l and R is the radius of the sphere to be examined. Advantageously, function $f_l(r)$ is used to adjust the depth weighing of a current distribution model.

Furthermore, the invention relates to a measurement device for determining the current distribution by measuring magnetic fields in the vicinity of the object. The measurement device includes a set of measurement channels that measure a curl free and divergence free vector field, whereby at least one measurement sensor corresponds to each channel, and processing means for processing the measurement signal. Advantageously, the object is approximated with a spherically symmetric conductor.

According to the invention, the processing means include a conversion module for converting a multi-channel measurement signal corresponding to each measurement sensor into the signal of a predetermined set of virtual sensors; and calculation means for determining the current distribution of an object being examined or for calculating by depth r from the sig-

nals of the set of virtual sensors in a beforehand selected orthonormal function basis. In one embodiment, the calculation means are arranged to calculate a multi-pole expansion from a multi-channel measurement signal.

The invention enables one to considerably lighten and accelerate the calculation associated with the modelling of a continuous current distribution. The invention further enables one to reduce the problems associated with noise. Further, the invention simplifies the regularisation of a source model, or eliminates the need for it, thus also significantly reducing the possibility of error.

LIST OF FIGURES

In the following, the invention will be described in detail by means of examples with reference to the accompanying drawing, in which

Fig. 1 represents one measurement device in accordance with the present invention; and

Fig. 2 is a flow chart illustrating one method in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 represents one measurement device in accordance with the present invention comprising a set of measurement channels 1^1, 1^2,...1^5 that measure a curl free and divergence free vector field, in which case at least one measurement sensor 2^1, 2^2,...2^5 corresponds to each channel; and processing means 3 for processing the measurement signal. Advantageously, the processing means have been implemented by means of a computer. Further, the processing means include a conversion module 4 for converting a multi-channel measurement signal corresponding to each measurement sensor into the signals of a predetermined set of virtual

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sensors, and calculation means 5 for determining the current distribution of an object being examined.

Further Fig. 1 shows the object being measured K, into the vicinity of which the measurement sensors 2^1, 2^2,...2^5 have been placed. Inside the object being measured there is presented a current loop which describes the source of the magnetic field being measured. The object being measured can be e.g. a human head, and there can be several current sources.

Fig. 2 represents the main steps of one preferred embodiment of the present invention. At first, a set of sensors is used to measure a multi-channel measurement signal, step 21. After that, the signal is converted to correspond to the signal measured using a so-called set of virtual sensors, step 22, making the mathematical operations simpler. Finally, it is possible to simply calculate the current distribution in an object from the signal of the set of virtual sensors, step 23, i.e. in practice, to describe the places and strengths of the current loops inside a sphere or head.

In the following section, the mathematical background and grounds of the invention are described. When the magnetic fields are converted into coefficients $M_{lm} = a_{lm} + ib_{lm}$ associated with the basic solution $r^{-(l+1)}Ylm(\theta,\varphi)$ of the Laplace equation, wherein i is an imaginary unit, they can be expressed by means of the current distribution $\vec{J}(\vec{r})$ in spherical coordinates (r,θ,φ), whereby they are of the form:

$$M_{lm} = \gamma_l \int_v r^l \vec{X}_{lm}(\theta,\varphi) \bullet \vec{J}(\vec{r}) dv \qquad (1),$$

wherein the integration is performed over the volume being examined, γ_l is a constant associated with order l and $\vec{X}lm(\theta,\varphi)$ is so-called vector spherical harmonic.

This form can be derived e.g. from publication "Multipole expansions of electromagnetic fields using Debye potentials", C.G. Gray, American Journal of Physics, Vol. 46, pp. 169-179, 1978. The expression mentioned above is of the lead field form, wherein the lead field of the multi-pole coefficient M_{lm} is of the form:

$$\vec{L}_{lm}(\vec{r}) = r^{l}\vec{X}_{lm}(\theta,\varphi) \qquad (2).$$

On the other hand, the vector spherical harmonics form by depth r an orthonormal basis, so with the depth in question, the current distribution can be presented in the function basis in question:

$$\vec{J}(\vec{r}) = \sum_{l=0}^{L}\sum_{m=-l}^{l} c_{lm} f_l(r)\vec{X}lm(\theta,\varphi) \qquad (3),$$

wherein $f_l(r)$ is some radical function.

When as the volume to be examined, spherical volume is selected, by placing the previous expression into the equation (1), the coefficients of the current distribution can be analytically solved:

$$c_{lm} = \hat{\gamma}_l M_{lm}\left[\int_0^R r^{l+2} f_l(r)dr\right]^{-1} \qquad (4),$$

wherein $\hat{\gamma}_l$ is a constant associated with order l and R is the radius of the sphere to be examined. The previous equation (4) indicates that the coefficients of a current distribution model presented in an orthonormal basis can be solved based on coefficients M_{lm} in a completely trivial manner using analytical expressions without any kind of regularisation. This is computationally very fast and numerically stabile. Function $f_l(r)$ is freely selectable,

and can be used to adjust the depth weighing of a current distribution model.

Furthermore, it must be noted that in the case of a spherical conductor, it is possible to use as basis functions also some other orthogonal basis or a basis whose inner products can be otherwise quickly calculated. This is achieved e.g. by slightly breaking the orthogonality in a manner known per se, or by using a basis which is not orthogonal but whose inner products can be calculated beforehand.

The invention is not limited merely to embodiment examples referred to above, instead many variations are possible within the scope of the inventive idea defined by the claims.

CLAIMS

1. A method for determining the current distribution of an object by measuring the magnetic fields in the vicinity of the object using a multi-channel measurement device that measures a curl free and divergence free vector field, whereby one measurement sensor corresponds to each channel, characterised in that

converting a multi-channel measurement signal corresponding to each measurement sensor into the signals of a predetermined set of virtual sensors, which signals are mutually orthogonal; and

determining the current distribution of an object being measured from the signals of the set of virtual sensors in a predetermined function basis to be efficiently calculated.

2. The method as defined in claim 1, characterised in that the object is approximated using a conductor, and a multi-pole expansion of the field is calculated from the multi-channel measurement signal.

3. The method as defined in claim 2, characterised in that the object is approximated using a spherically symmetric conductor.

4. The method as defined in claim 2, characterised in that the multi-pole expansion is calculated by taking into account the magnetic fields emitted by sources outside the object.

5. The method as defined in claim 2, characterised in that the multi-pole expansion is calculated by ignoring the magnetic fields emitted by sources outside the object.

6. The method as defined in claim 2, characterised in that the external interferences are eliminated using some other known interference eliminating method prior to the conversion.

7. The method as defined in claim 2, characterised in that as the orthonormal function basis, a current distribution equation of the following form is selected:

$$\vec{J}(\vec{r}) = \sum_{l=0}^{L} \sum_{m=-l}^{l} c_{lm} f_l(r) \vec{X}lm(\theta,\varphi) ,$$

wherein c_{lm} are coefficients of the current distribution, $f_l(r)$ is a freely selectable radial function and $\vec{X}lm(\theta,\varphi)$ is so-called vector spherical harmonic.

8. The method as defined in claim 5, characterised in that

the orthonormal function basis is placed into a current distribution equation; and

the coefficients of the current distribution are analytically solved from the equation:

$$c_{lm} = \hat{\gamma}_l M_{lm} \left[\int_0^R r^{l+2} f_l(r) dr \right]^{-1} ,$$

wherein $\hat{\gamma}_l$ is a constant associated with order 1, M_{lm} are multi-pole coefficients, R is the radius of the sphere to be examined, and $f_l(r)$ is a freely selectable radial function.

9. The method as defined in claim 7, characterised in that function $f_l(r)$ is used to adjust the depth weighing of the current distribution model.

10. A measurement device for determining the current distribution of an object by measuring magnetic fields in the vicinity of the object, the measurement device comprising:

a set of measurement channels ($1, 1^1, 1^2, \ldots 1^n$) that measure a curl free and divergence free vector field, in which case at least one measurement sensor $2, 2^1, 2^2, \ldots 2^4$ corresponds to each channel; and

processing means (3) for processing the measurement signal and in which the object is approximated using a conductor, c h a r a c t e r i s e d in tha:

the processing means include a conversion module (4) for converting a multi-channel measurement signal corresponding to each measurement sensor into the signals of a predetermined set of virtual sensors, which signals are mutually orthogonal; and

calculation means (5) for determining the current distribution of an object being examined from the set of virtual sensors using depth r in a predetermined orthonormal function basis.

11. The measurement device as defined in claim 10, c h a r a c t e r i s e d in that the calculation means (5) are arranged to calculate a multipole expansion from the multi-channel measurement signal.

12. The measurement device as defined in claim 10, c h a r a c t e r i s e d in that the object is approximated using a spherically symmetric conductor.

13. The measurement device as defined in claim 11, c h a r a c t e r i s e d in that the multipole expansion is calculated by taking into account the magnetic fields emitted by sources outside the object being measured.

14. The measurement device as defined in claim 11, c h a r a c t e r i s e d in that the multipole expansion is calculated by ignoring the magnetic fields emitted by sources outside the object being measured.

15. The measurement device as defined in claim 11, c h a r a c t e r i s e d in that as the orthonormal function basis, a current distribution equation with the following form is selected:

$$\vec{J}(\vec{r}) = \sum_{l=0}^{L} \sum_{m=-l}^{l} c_{lm} f_l(r) \vec{X}lm(\theta, \varphi),$$

wherein c_{lm} are coefficients of the current distribution, $f_l(r)$ is a radial function to be freely selected and $\vec{X}lm(\theta,\varphi)$ is so-called vector spherical harmonic.

16. The measurement device as defined in claim 14, characterised in that

the orthonormal function basis is placed into the current distribution equation; and

the coefficients of the current distribution are solved analytically from the equation:

$$c_{lm} = \hat{\gamma}_l M_{lm} \left[\int_0^R r^{l+2} f_l(r) dr \right]^{-1},$$

wherein $\hat{\gamma}_l$ is a constant associated with order l, M_{lm} are multi-pole coefficients, R is the radius of the sphere to be examined and $f_l(r)$ is a radial function to be freely selected.

17. The measurement device as defined in claim 15, characterised in that function $f_l(r)$ is used to adjust the depth weighing of a current distribution model.

18. The measurement device and analysis software as defined in claim 10, wherein the measurement device converts the signals into a set of virtual sensors prior to their storage, and the analysis software converts the stored data into a current distribution.